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Design and Characterization of a New Three-Stage Quadruple Pass EDFA

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Abstract: Low loss long haul Optical Fiber Communication System (OFCS) is the key challenge in today's research. Multi-stage Erbium-Doped Fiber Amplifier (EDFA) provides high gain, low noise figure and long distance transmission. Development of multi-stage EDFAs has become one of main research areas in recent times. In this study, a three-stage Quadruple Pass (QP) EDFA is proposed for long haul OFCS. The mathematical models to characterize this proposed EDFA are developed. In the mathematical models, the effects of Amplified Spontaneous Emission (ASE) of prior stages are included. Performance analysis of this QP EDFA is carried out with the variation of input pump power ratio and signal power. A maximum gain of 59.94 dB is achieved corresponding -33 dm input signal power at 1550 nm wavelength. Change in erbium ions concentration in energy level 1 (N1) and energy level 2 (N2) with the variation of fiber length is also analyzed to determine optimum fiber length. From the obtained results the optimum design parameters (pump power, signal power, fiber length) are recommended for practical implementation.

Key words: Quadruple pass, noise figure, optimum length, design parameters, transmission

INTRODUCTION

Invention of EDFAs in the 1980s is considered as a major breakthrough for the development of optical communications (Becker *et al*., 2002). Erbium Doped Fiber Amplifiers (EDFA) is used in the system simulations because of its ability to provide high gain, low noise figure and wide bandwidth. A long haul high bit-rate transmission within the optical transmission bandwidth can be achieved using EDFAs (Keiser, 2000). There are numerous researches were carried out on one-stage EDFAs and there is well-established mathematical model for that. However, there is very few research are done to design and characterize multi-stage EDFAs. The main purpose of designing multi stage EDFAs is to achieve higher gain and lower Noise Figure (Becker *et al*., 2002; Desurvire, 2002) and as a consequence, researchers are seeking interest to work on multi-stage (triple pass, quadruple pass etc.) these days. Some researches are done on multi-stage EDFAs including Quadruple Pass (QP) EDFA. Ali *et al.* (2009) proposed an a design of two stage quadruple pass configuration. Performances of the EDFA were analyzed with the variation pump powers and signal powers. However, the length of the EDFs were not optimized.

Naji *et al.* (2010) proposed two Triple Pass (TP) EDFAs that were named as A and B. Impact of variation of pump power and signal power were analyzed for the proposed EDAs.

Configuration B provided with higher gain configuration than A. However, values of noise figures were almost same. Analyzing the performances, configuration B was recommended for better optical signal amplification. However, the ASE effect was not included for the calculation second stage EDF. Moreover, input pump power and fiber length were not optimized for the proposed design.

Qin *et al.* (2010) proposed a novel design of three-stage L-band EDFA structure with ASE pumping. On the basis of the Giles model with ASE, characteristics of the proposed EDFA were studied. From the obtained results, it found that it can provide 33.4 dB gain with only about 1 dB gain ripple and less than 4.5 dB noise figure (from 1570-1605 nm) when the input signal was fixed at -30 dBm. However, design parameters (EDF length and input pump power) were not determined.

Previous studies that developed QP EDFA were in two-stage whereas QP EDF A can be configured in three-stage. However, the performances of three-stage EDFAs are not explored yet. This study represented a new three-stage Quadruple Pass (QP) EDFA. The modified mathematical models are described and performances of this QP EDFA are analyzed and the optimum parameters are determined for practical design. Comparing the existing QP EDFAs with our proposed one, significance of this research is highlighted.

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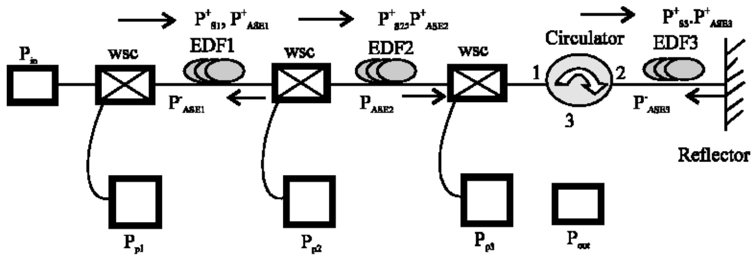

Fig. 1: Forward pumped three-stage quadruple pass erbium doped fiber amplifier

QUADRUPLE PASS EDFA

In the proposed three-stage QP EDFA, there are three EDFs are connected in such a way that signal passes once through first and second erbium-Doped Fiber (EDF) and twice through the third EDF. At the end of third EDF, a mirror is connected so that signal reflected by the mirror passes again through that EDF to amplify the signal two times. The total number of passes through the EDF is four in the whole amplification scheme that is why it is called quadruple pass EDFA. The output signal power of the first stage is the input signal power for the second stage and the output signal power of the second stage is the input signal power for the third stage. Figure 1 shows the schematic diagram of forward pumped QP EDFA configuration.

Figure 1 Wavelength Selective Coupler (WSC) is used to multiplex and demultiplex the signal and pump lights. A Circulator (Cir) is used as an isolator and at the same time to separate the input signal from the output signal. It is also utilized to minimize the effect of multipath interference noise in the transmission line.

MATHEMATICAL MODEL

It has been assumed that it uses a pump wavelength of 1480 nm. The two energy levels system is considered and the Er^{3+} ions densities of upper state population (N_2) and ground state population (N_1) being calculated as follows (Giles and Desurvire, 1991):

$$N_1 = \rho\frac{1+W_{12}\tau}{1+(W_{12}+W_{21})\tau+R\tau} \tag{1}$$

$$N_2 = \rho\frac{R\tau+W_{21}\tau}{1+(W_{12}+W_{21})\tau+R\tau} \tag{2}$$

where, W_{12} and W_{21} are the stimulated absorption rate and stimulated emission rate, respectively, R is the pumping rate, τ is the fluorescence lifetime and $\rho = N_1+N_2$ is the Er^{3+} ions density per unit volume. The value of W_{12} and W_{21} of the first Single Pass (SP) EDF can be calculated as (Giles and Desurvire, 1991):

$$W_{12} = \frac{\sigma_{SA}(\lambda_s)\Gamma_S}{hV_S A}(P^+_{S1} + P^+_{ASE1} + P^-_{ASE1}) \tag{3}$$

$$W_{21} = \frac{\sigma_{SE}(\lambda_s)\Gamma_S}{hV_S A}(P^+_{S1} + P^+_{ASE1} + P^-_{ASE1}) \tag{4}$$

For the second SP EDF, the equations for W_{12}, W_{21} are modified as follows:

$$W_{12} = \frac{\sigma_{SA}(\lambda_s)\Gamma_S}{hV_S A}(P^+_{S2} + P^+_{ASE2} + P^-_{ASE2} + P^+_{ASE1}) \tag{5}$$

$$W_{21} = \frac{\sigma_{SE}(\lambda_s)\Gamma_S}{hV_S A}(P^+_{S2} + P^+_{ASE2} + P^-_{ASE2} + P^+_{ASE1}) \tag{6}$$

For the third Double Pass (DP) EDF, the equations for W_{12}, W_{21} are modified as follows:

$$W_{12} = \frac{\sigma_{SA}(\lambda_s)\Gamma_S}{hV_S A}(P^+_{S3} + P^-_{S3} + P^+_{ASE3} + P^-_{ASE3} + P^+_{ASE2}) \tag{7}$$

$$W_{21} = \frac{\sigma_{SE}(\lambda_s)\Gamma_S}{hV_S A}(P^+_{S3} + P^-_{S3} + P^+_{ASE3} + P^-_{ASE3} + P^+_{ASE2}) \tag{8}$$

The value of R for all EDF can be calculated as (Giles and Desurvire, 1991):

$$R = \frac{P_P^- \Gamma_P \sigma_P}{hV_P A} \tag{9}$$

where, σ_{ES} and σ_{SA} are the emission and absorption cross-sections of the signal, while and σ_{PE} and σ_{PA} are the emission and absorption cross-sections of the pump. V_S and V_P are the signal and pump frequencies, respectively. Γ_S and Γ_P are the overlap factors of the signal and the pump, respectively. It represents the overlap of the erbium ions with the mode of the signal light field and pump light field, respectively. A is the effective cross-sectional area of the distribution of erbium ions, h is the

Planck constant, P^{+}_{S} is the forward signal power and P_P is the pump power of the EDFA. P^{+}_{ASE} and P^{-}_{ASE} are the forward and backward spontaneous emission powers of the EDFA, respectively (Giles and Desurvire, 1991; Qinghe *et al*., 1999):

$$\frac{d_P^{P+}}{dz} = P_P^{+}\Gamma_P(\sigma_{PE}N_2 - \sigma_{PA}N_1) - \alpha_P P_P^{+} \tag{10}$$

$$\frac{dP_S^{+}}{dz} = P_S^{+}\Gamma_S(\sigma_{SE}N_2 - \sigma_{SA}N_1) - \alpha_S P_S^{+} \tag{11}$$

$$\frac{dP_{ASE}^{+}}{dz} = P_{ASE}^{+}\Gamma_S(\sigma_{SE}N_2 - \sigma_{SA}N_1) + 2\sigma_{SE}N_2\Gamma_S hV_s\Delta v - \alpha_S P_{ASE}^{+} \tag{12}$$

$$\frac{dP_{ASE}^{-}}{dz} = -P_{ASE}^{-}\Gamma_S(\sigma_{SE}N_2 - \sigma_{SA}N_1) - 2\sigma_{SE}N_2\Gamma_S hV_s\Delta v + \alpha_S P_{ASE}^{-} \tag{13}$$

where, Δv is the bandwidth of the ASE, z is the co-ordinate along the EDF, α_S and α_p represents the internal signal and pump loss term of the amplifier, respectively.

During the reflection by the fiber loop mirror, a reflection loss (R_{LOSS}) to the amplified P^{+}_{S} is considered. (R_{LOSS}) is calculated as (Qinghe *et al*., 1999):

$$R_{Loss} = 4K(1-K)(1-\Gamma)^2 e^{L\alpha} \tag{14}$$

where, K, Γ and αL and the attenuation induced by the fiber loop. Noise figure is closely related to ASE which is generated by spontaneous emission and the number of spontaneous photons is given by Qinghe *et al*. (1999):

$$\eta_{SP} = \frac{\eta N_2}{\eta N_2 + N_1} \tag{15}$$

where, η_{Sp} is known as the spontaneous emission factor and $\eta = \sigma_{SE}/\sigma_{SA}$. The noise figure of the EDFA ($NF^{Er}(\lambda_S)$) at the signal wavelength λ_S can be calculated as (Qinghe *et al*., 1999):

$$NF^{Er}(\lambda_S) = \frac{1 + 2\eta_{Sp}[G_{EDFA} - 1]}{G_{EDFA}} \tag{16}$$

For high gain condition (G_{EDFA}>20 dB) equation can be written as (Qinghe *et al*., 1999):

$$NF^{Er}(\lambda_S) \approx 2\eta_{SP} \tag{17}$$

RESULTS AND DISCUSSION

The performance analysis of the proposed QP EDFA has been carried out with the variation of pump power, signal power. The effect on the number of erbium ions concentration in energy level 1(N1) and 2 (N2) with the variation of fiber length has also been analyzed to determine the optimum fiber length. Figure 2 shows gain performance of proposed QP EDFA with the variation of pump power ratio.

To analyze the performance of EDFA, the first pump power is varied from 20-150 mW, second pump power from 110-240 mW and third pump power from 160-290 mW. From Fig. 2, it is clear that with the increase in input pump power both Gain and noise figure are increasing. However, after the pump power ratios 100:190:240 mW, the changes are quite steady state. For 100:190:240 mW, obtained gain and noise figures are 59.73 dB and 11.88 dB whereas for 100:200:250 (mW), the values of gain and noise figures are 59.94 and 11.92 dB, respectively. For a gain enhancement of 0.21 dB, noise figure is also increased of an amount 0.06 dB. With the increase of input pump power, the change in output is not too high. Therefore, it can be concluded that the optimum pump power ratio for the proposed QP EDFA is 100:190:240 mW. This result signifies the importance of choosing input pump power. If the input pump power ratio is 100:190:240, this EDFA will provide the maximum efficiency.

Figure 3 shows the gain and noise figure performance of proposed QP EDFA with the variation of signal power. As the signal power increases, the value of gain decreases and noise figure increases. For input signal power of -50 dBm, values of gain and noise figure are

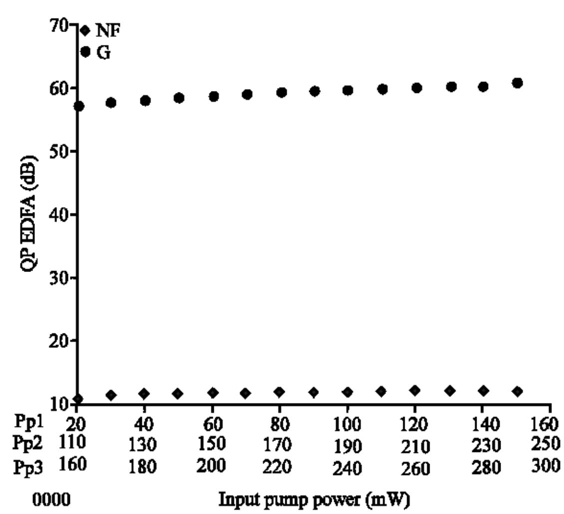

Fig. 2: Gain (G) and noise figure (NF) performance of the proposed QP EDFA with the variation of pump power ratio corresponding to -50 dBm input signal power at λ = 15550 nm

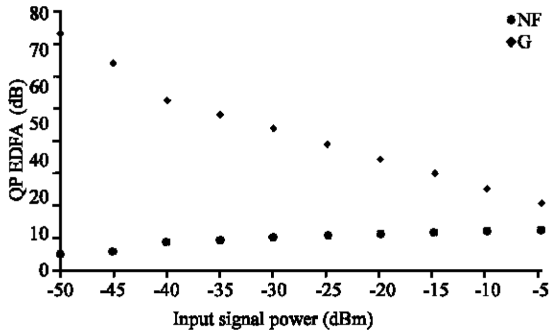

Fig. 3: Gain and noise figure performance of the proposed QP EDFA with the variation of signal power at λ = 15550 nm

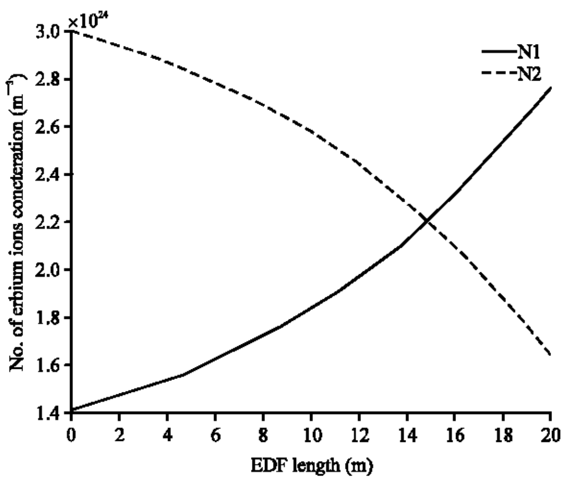

Fig. 4: Upper state population (N2) and ground state population (N1) as a function of fiber length for the second EDF at 10 mW pump power and 33 dBm signal power

72.86 and 5.06 dB whereas for -45 dBm input signal power, values of gain and noise figure are 63.74 and 6.01 dB, respectively. For 5 dBm input signal power, values of gain and noise figure are 20.61 and 12.60 dB, respectively. It is clear from figure 3 that the lower signal power, the better performance of EDFA. Therefore, it can be concluded that the optimum signal power of the proposed QP EDFA is -50 dBm.

Figure 4 shows the change in erbium ions concentration in energy level 1 (N1) and energy level 2 (N2) with the variation of fiber length. Here, due to low input pump power N1 and N2 intersect each other at fiber length 15 m. This means the optimum length of the first SP EDF of QP EDFA is 15 m.

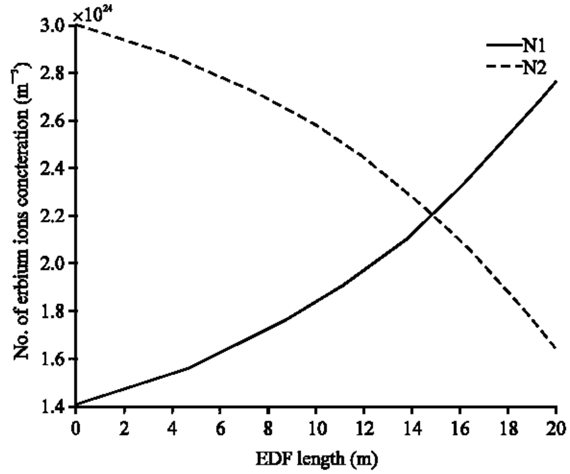

Fig. 5: Upper state population (N2) and ground state population (N1) as a function of fiber length for the first EDF at 10 mW pump power and -33 dBm signal power

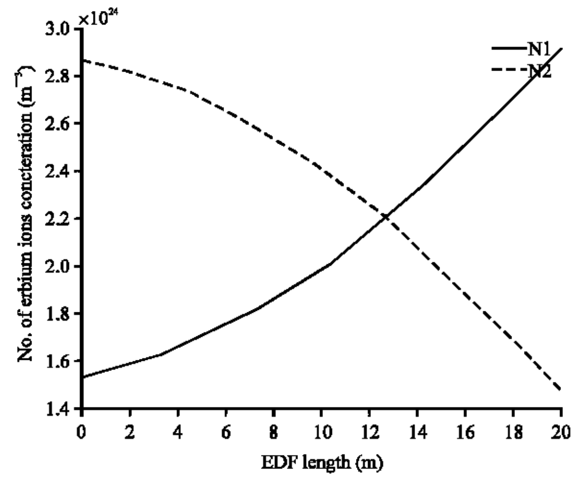

Fig. 6: Upper state population (N2) and ground state population (N1) as a function of fiber length for the third EDF at 10 mW pump power and -33 dBm signal power

Figure 5 shows the erbium ions concentration versus fiber length curve for the second SP EDF of the proposed three-stage configuration. Here, N1 and N2 intersect each other fiber length 15 m due to insufficient pump power. This means the optimum length of the second SP EDF of QP EDFA is 15 m.

Figure 6 shows the erbium ions concentration versus fiber length curve for the third DP EDF of QP EDFA. Here, N1 and N2 intersect each other fiber length 13 m due to insufficient pump power. This means the optimum length of the third DP EDF of QP EDFA is 15 m.

In our study, methods of determining the optimum design parameters are shown. Without optimizing the parameters, implementation of any EDFA is not cost-effective. Al-Khateeb *et al.* (2006) proposed a Quadruple-Pass Amplification (QPA) in a Dual-Stage, using a fiber loop-back and a tunable band pass filter (TBF). High gain value of 54 dB was obtained at 10 mW and 90 mW pump powers in the first and second stages respectively, correspond to -50 dBm input signal power. However, usage of three circulators and two TBFs made the implementation expensive. Moreover, EDF length and input pump power was not optimized before experimental setup.

Ali *et al.* (2009) achieved a maximum gain of 60 dB at 980 nm pump. However, using three stage schemes, it is possible to obtain the same value of gain at 1550 nm pump. Moreover, 980 nm pumps are not readily available these days, so it is not a good idea to use 980 nm pump rather than 1550 nm. There is one more issue; they didn't determine the optimum fiber length before developing it practically. Determining optimum fiber length corresponding to a certain input pump power is a very important criterion before implementation. If the input power is less than optimum, then it cannot excite the atoms of the whole length of the fiber, as a result EDFA gain decreases and noise figure increases. On the other hand, if the pump power is higher than the optimum then, a portion of the pump power will remain unused which can cause more population inversion and hence the increment of the gain. In this case, though the gain is high, there is wastage of pump power.

Bouzid (2010) proposed a new Dual-Stage Quadruple Pass (DSQP) EDFA with filter. The signal experiences four amplifications in both stages with an efficient suppression of ASE by two tunable band pass filters. A high gain of 62.56 dB and a low NF of 3.98 dB were achieved at 175 mW pump power correspond to -50 dBm input signal power. However, addition of two circulators and two TBFs made this EDFA expensive to implement.

Naji *et al.* (2011) proposed a new model of two-stage EDFA. Using this configuration it is possible to obtain 60 dB gain corresponding to -50 dBm input signal at 1550 nm. However, usage of three circulators and two TBFs made the system expensive. Moreover, insertion loss of these components is high.

Whereas, in our proposed configuration, there is only one circulator, no TBF and able to provide the same gain and noise figure as the design proposed by Ali *et al.* (2009), Bouzid (2010) and Naji *et al.* (2011). The QP EDFA designed by Al-Khateeb *et al.* (2006) provides lower gain than our proposed one. Therefore, it can be concluded that our proposed QP EDFA is the most cost-effective design for practical implementation.

CONCLUSION

Modeling and performance analysis of the proposed three-stage QP EDFA is successfully demonstrated in this paper. While developing mathematical models, ASE effects of first-stage are added in the second and third-stage in order to achieve more accurate results. Performance analysis of the proposed EDFA is carried out with the variation of design parameters (Pump power, signal power). For a low input pump power (20 mW), very high gain (57.11 dB) can be achieved using the proposed QP scheme. In this way, the repeaters distance can be increased. Finally, it can be said that this proposed QP EDFA will be a right choice for a practical long haul optical communication.

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